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Burning Behavior of Gun Propellants under the Influence of Pressure Oscillations Theoretical Background and Simulation

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Introduction

During the last 15 years a lot of experimental and some theoretical work has been done in Germany to investigate pressure oscillations which can be seen when single or multi perf propellants are tested in closed vessels.

From the experimental work there is strong evidence that these pressure oscillations are correlated to standing density waves in the perfs arising from a wide spectrum of initial perturbations which occur when the flame ingresses into the perfs of the propellant grains.

Experimental Results

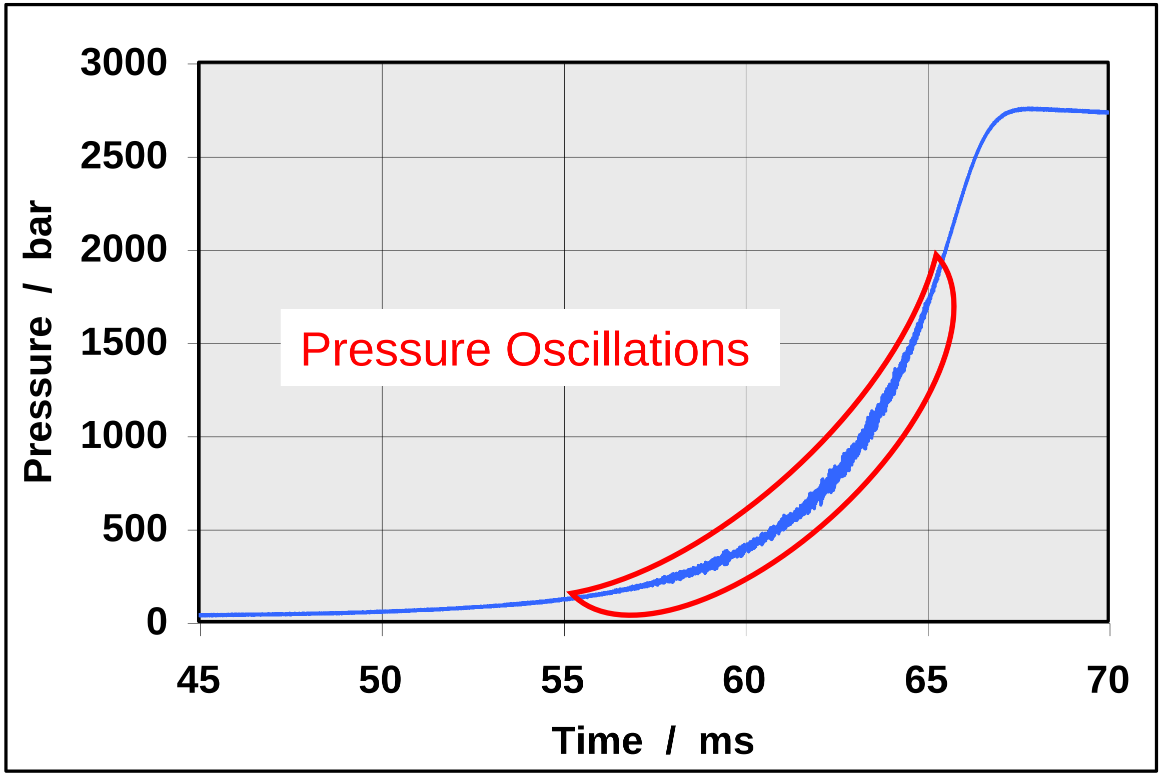
Experimental Results

Closed Vessel Test of a 19 perf Gun Propellant

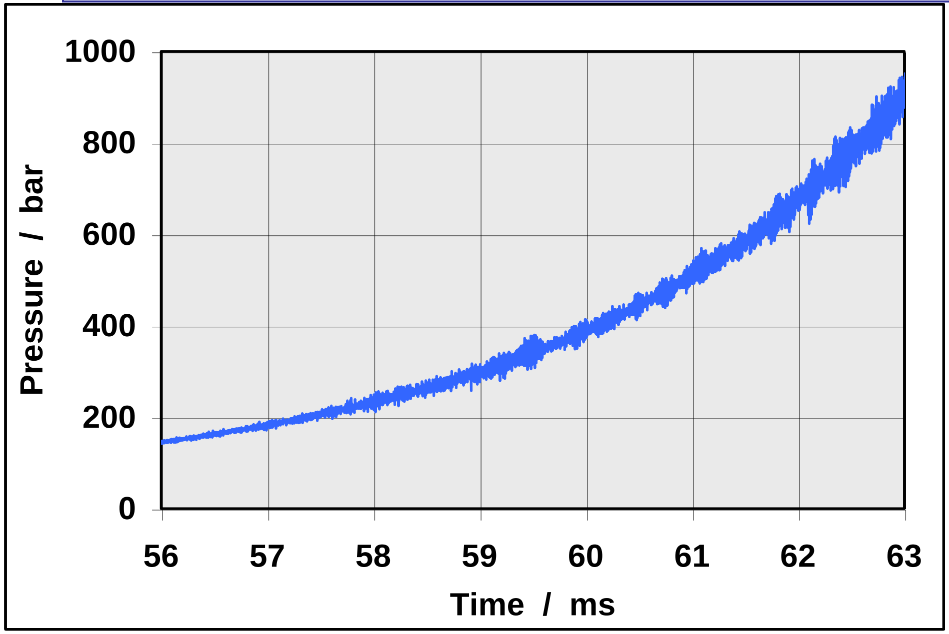
Dimensions: L ≈ 18.7 mm
D ≈ 13.3 mm
d ≈ 0.26 mm

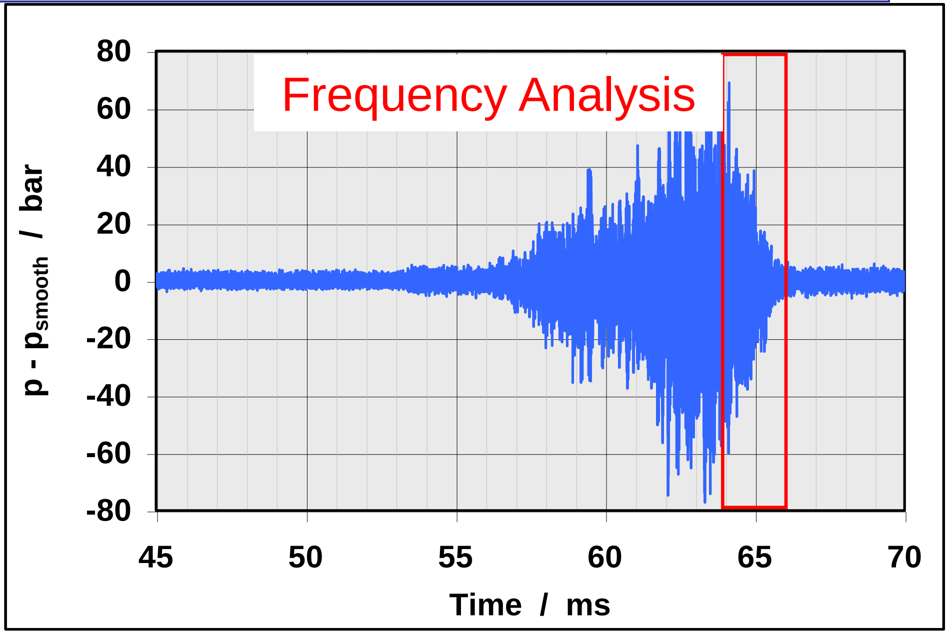
Recipe:		
	NC	≈ 68.4 %
	NGL	≈ 29.0 %
	Plasticizer	≈ 1.3 %
	Stabilizer	≈ 1.3 %

CV 200 ml, Loading Density ≈ 0.2 g/cm³, T_c = -40 °C

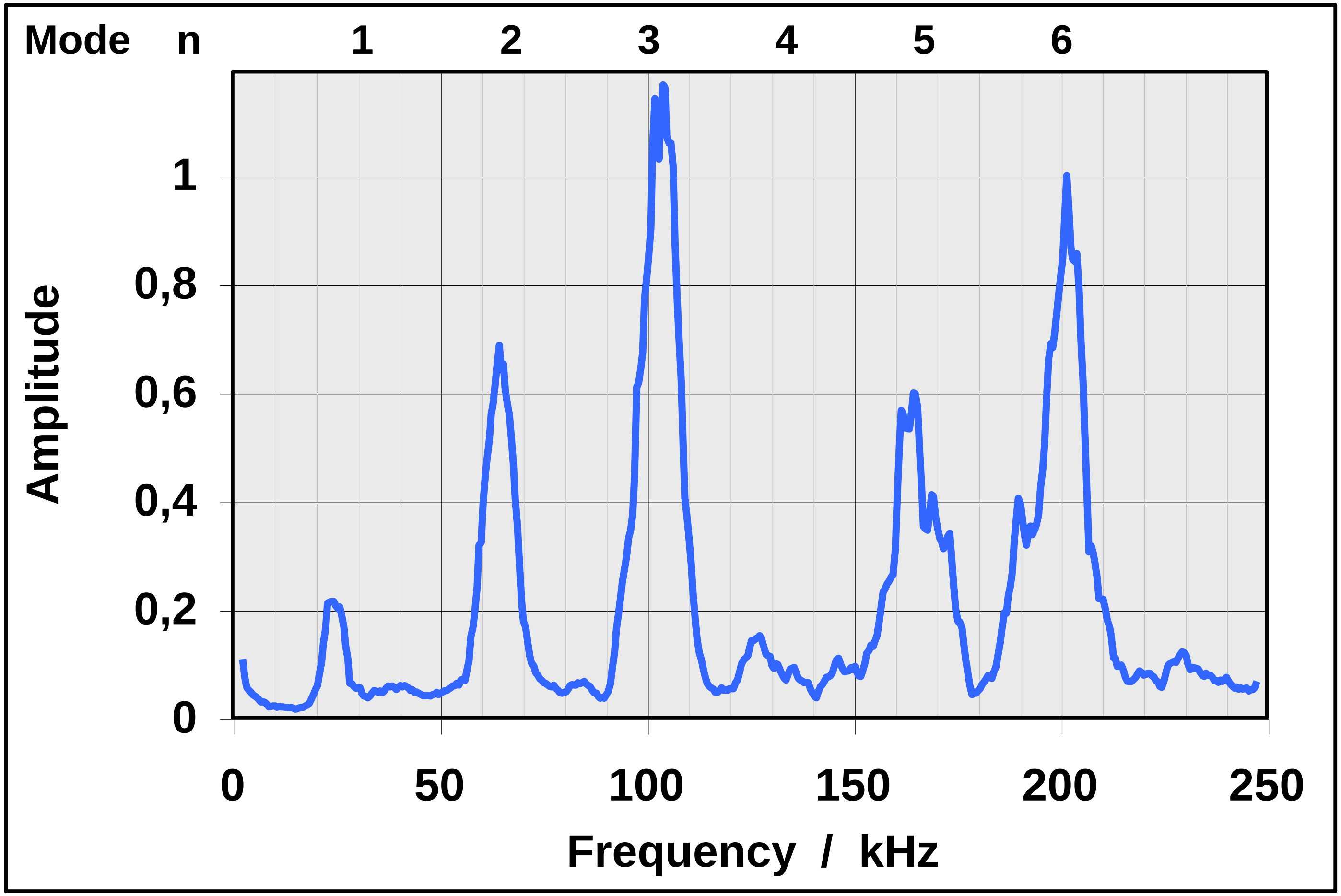


Experimental Results



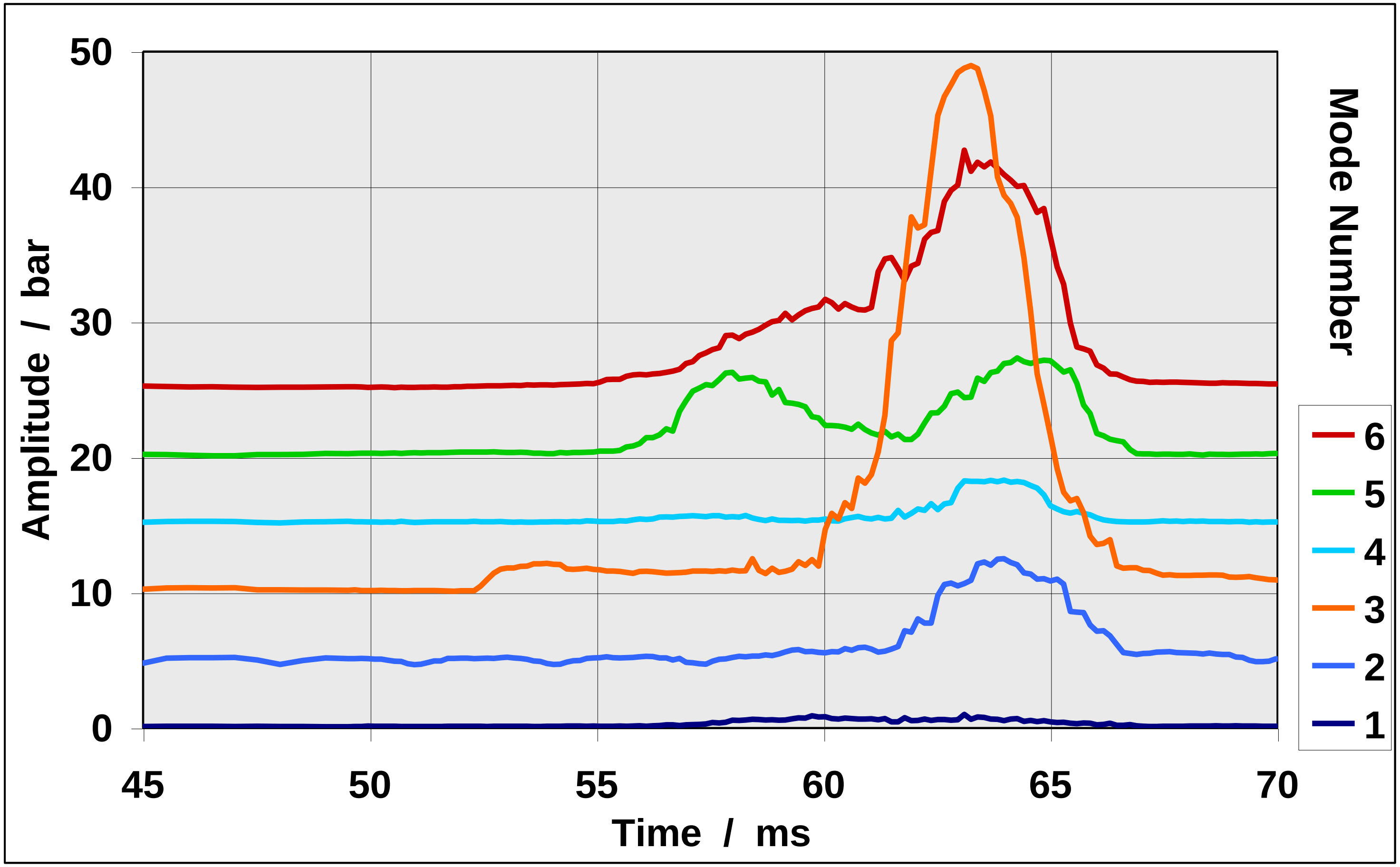


Experimental Results



High amplitudes occur at frequencies f which correlate with the velocity of sound c_s and the length L of the grain: $f \approx n \cdot c_s / 2L'$

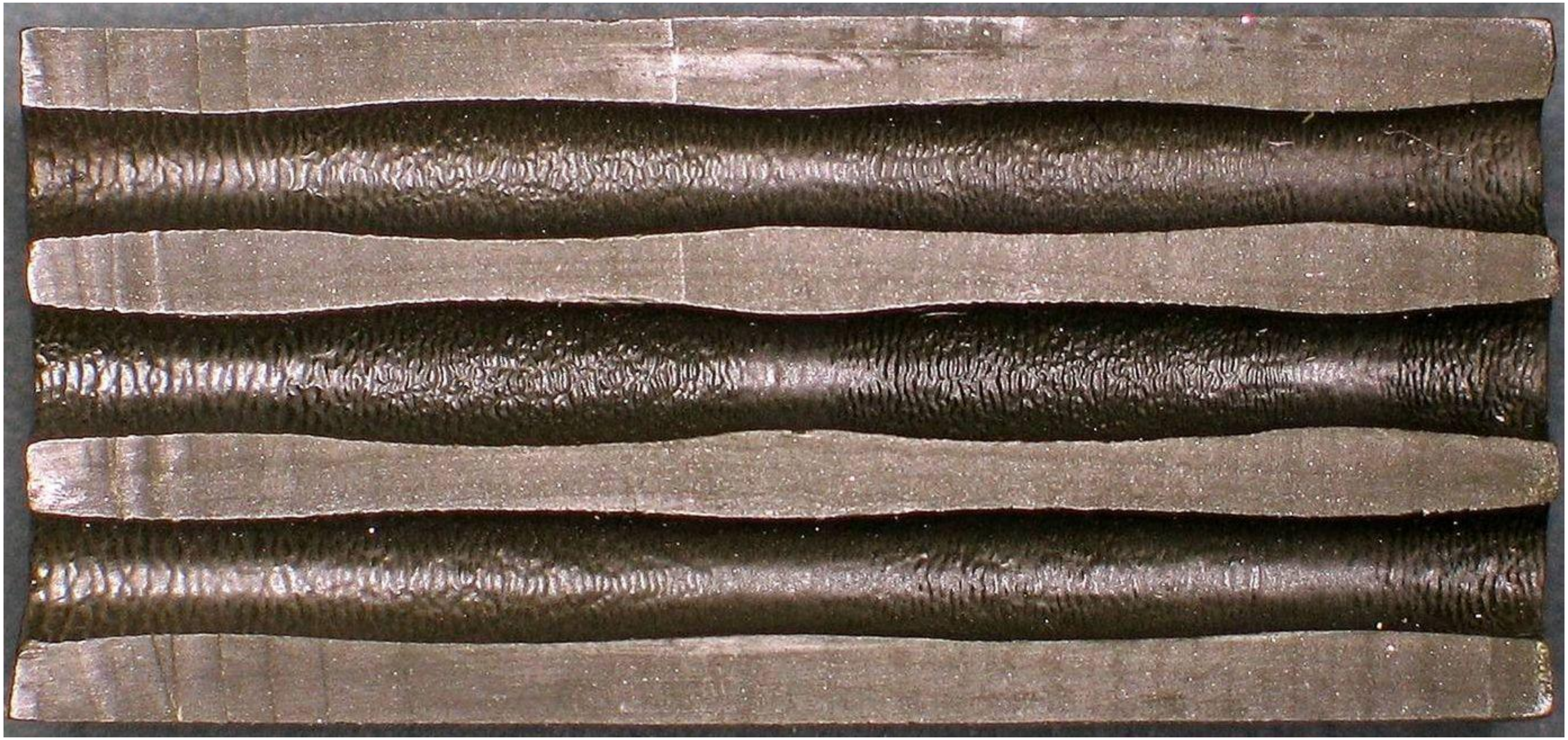
Experimental Results



Time dependence of the amplitudes of different modes.
In the given example mode 3 is the dominant mode.

(n-1)•5 bars are added to the amplitudes of each mode to make the figure more readable.

Experimental Results



Cross sectional view of a propellant grain after burning interruption test with typical anomalous wavelike perf geometry indicating regions of increased gas production rates correlated to a dominant mode 3.

Theoretical Approach

Modeling of standing pressure waves in the perfs of gun propellant grains

Basis are the standard gasdynamic equations for solid and gas phase which are simplified for closed vessel application.

The goal was to get an analytic solution which describes standing waves in the perfs of gun propellant grains.

Therefore we assume that the solution can be written as series expansion with respect to a formal parameter ε, e. g. $\rho(\underline{r},t) = \rho_0(\underline{r},t) + \varepsilon^1\,\rho_1(\underline{r},t) + \varepsilon^2\,\rho_2(\underline{r},t) + \ldots$

and get a hierarchy of equations with respect to powers of ε.

Using suitable approximations and linearization we get solutions for the lowest order perturbation quantities

ρ_1 (density perturbation)

$v_{1,y}$ (velocity perturbation in axial direction)

Modeling of standing pressure waves in the perfs of gun propellant grains

$$\rho_{1,n}(y,t) \approx \rho_0^* \begin{Bmatrix} \cos(k_n y) \\ \sin(k_n y) \end{Bmatrix} \cos(\Omega_n t)\, e^{½\mu t} \qquad \begin{matrix} n \text{ odd} \\ n \text{ even} \end{matrix}$$

$$v_{1,y,n}(y,t) \approx c_s \begin{Bmatrix} \sin(k_n y) \\ -\cos(k_n y) \end{Bmatrix} \sin(\Omega_n t)\, e^{-½\mu t} \qquad \begin{matrix} n \text{ odd} \\ n \text{ even} \end{matrix}$$

$\Omega_n = \pi n c_s / L'$

$k_n = 2\pi/\lambda_n$, $\lambda_n = 2L'/n$

$L' = L + ¼\, \pi\, d_{perf}$ (accoustic length)

Two time scales:

Slow time ~ $1/\mu$

Fast Time ~ $½L'/c_s$

Within the framework of the used approximations the perturbation solution of the pressure p_1 is simply given as

$$p_1 = c_s^2\, \rho_1$$

Impact of standing pressure waves on the burning behavior in the perfs

The first idea was that the pressure oscillations directly cause a locally increased burning velocity according to the modified pressure which yields

$$de/dt = (de/dt)_o + (de/dt)_1 = \dot{e}(p_{Ref})\ \left(p_o + \varepsilon\, p_1 \right) / p_{Ref}$$

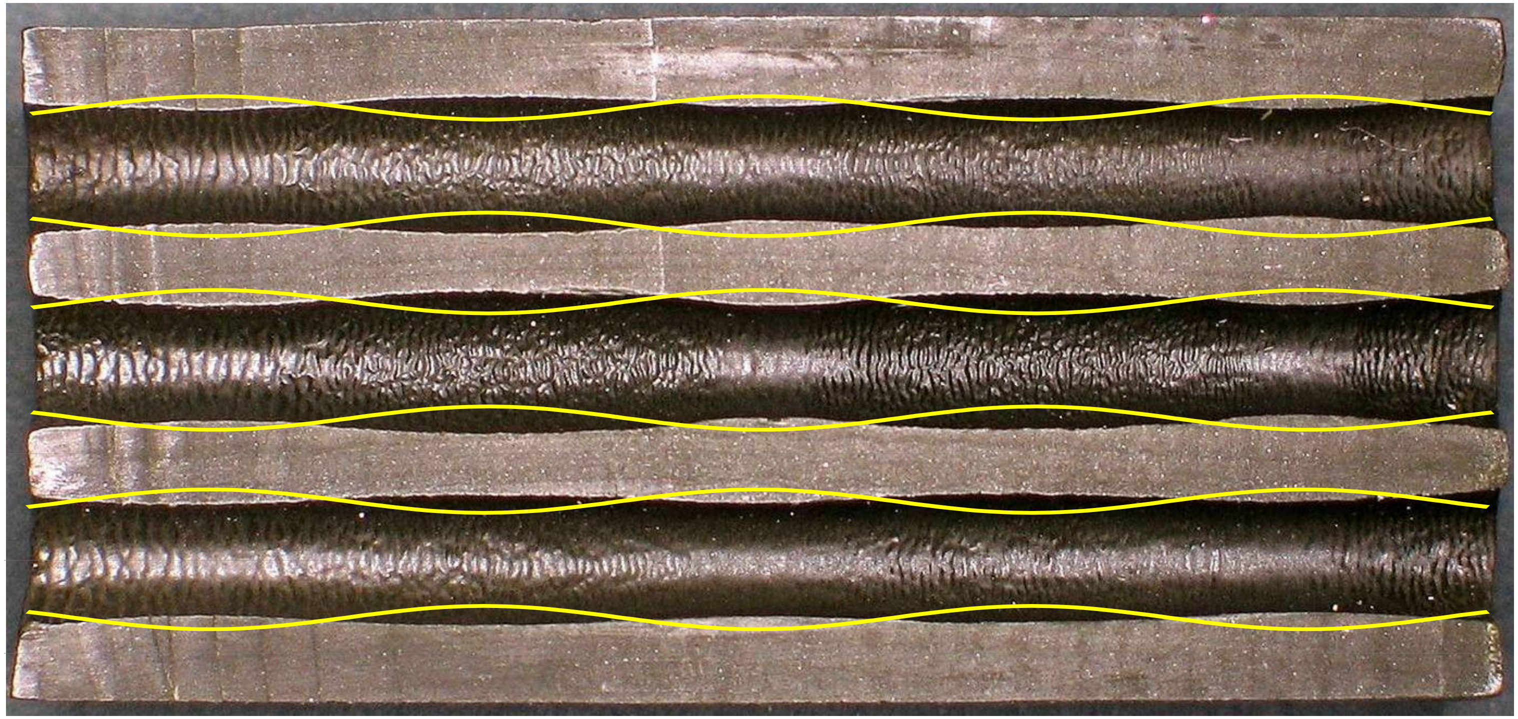
But averaging p_1 over one time period yields a quantity proportional to $\frac{1}{2}\mu/\Omega \bullet (\ \dots\ )$ which is close to zero.
So, no significant change of the burning velocity results.

The general momentum balance equation allows the determination of an approximate nonlinear solution $p_{1,nl}$ (known as acoustic radiation pressure) which yields a significant net effect after averaging over one time period

$$p_{1,nl} = \frac{1}{4}\ \varepsilon^2\, c_s^{\,2}\, \rho_o^* \begin{Bmatrix} \cos^2(k_n y) \\ \sin^2(k_n y) \end{Bmatrix} \qquad \begin{matrix} n \text{ odd} \\ n \text{ even} \end{matrix}$$

Impact of standing pressure waves on the burning behavior in the perfs

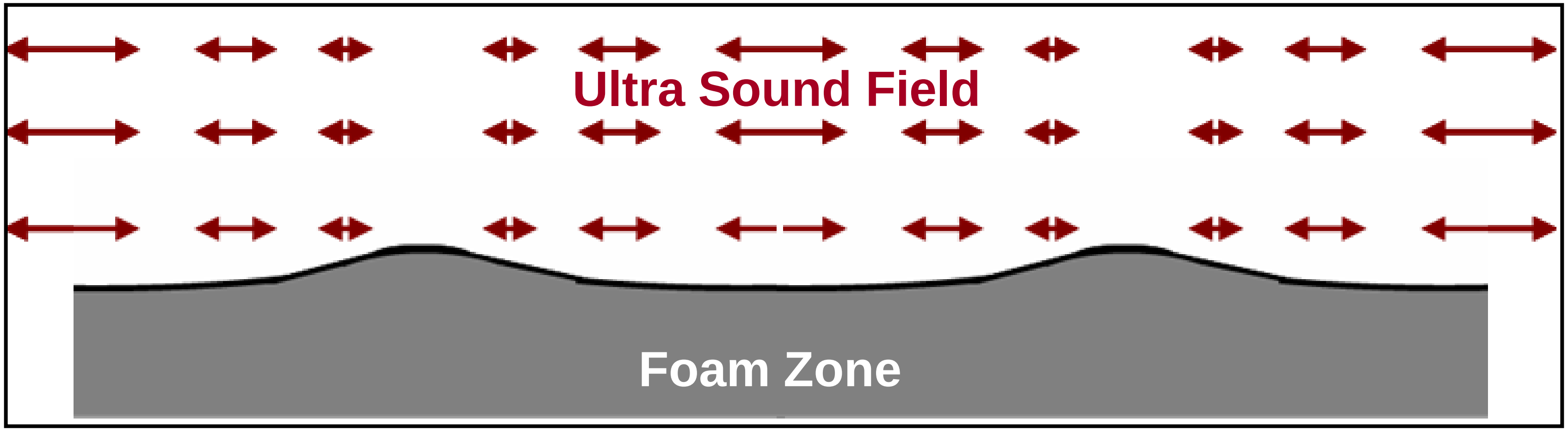
But this solution as well as the linear one show a wrong phasing, i. e. they have pressure nodes which means no enhanced burning at the end of the perfs whereas the experimental results always show antinodes at these locations.



So, the experimentally observed anomalous wavelike perf structure can not be explained as a direct impact even of the accoustic radiation pressure.

Alternative model to explain the anomalous burning behavior in the perfs

We propose that the anomalous burning behavior in the perfs of single or multi perf gun propellant grains is caused by the impact of the ultra sound velocity field $v_{1,y}$ on the thermally isolating foam zone which separates the solid phase of the propellant and the combustion gas phase. The very intensive ultra sound field locally reduces the thickness of this foam zone for instance by cavitation processes and therefore causes an increased heat flow into the unreacted cold propellant. Consequently, an increased gas production rate should occur at positions with high amplitudes of the ultra sound field.



Alternative model to explain the anomalous burning behavior in the perfs

The influence of thickness of the foam zone on the burning velocity can be derived from a simple heat balance. To heat up the small propellant element S•de from T_P to $T_{S,P}$ the heat power

$$dQ/dt = dm/dt\ c_p\ (T_{S,F} - T_P)$$

is necessary ($dm/dt = \rho_P\ S\ de/dt$, S burning surface area, c_p specific heat of the propellant). This heat power must be generated by the heat flow from the foam surface to the propellant element S•de

$$dQ/dt = \lambda_F\ S\ (T_{S,F} - T_P) / D_F$$

(λ_F heat conductivity, D_F thickness of the foam zone). Equating the two expressions yields an equation for the burning velocity de/dt as function of the foam zone thickness:

$$de/dt = \lambda_F / [\rho_p\ c_p\ D_F]$$

Alternative model to explain the anomalous burning behavior in the perfs

Without impact of ultra sound field (regular case) the thickness of the foam zone should be $D_{F,Ref}$ at reference pressure to get the usual burning law. This implies:

$$D_F = D_{F,Ref} / (p/p_{Ref})^{\alpha}$$

At presence of an ultra sound field with an acoustic energy density

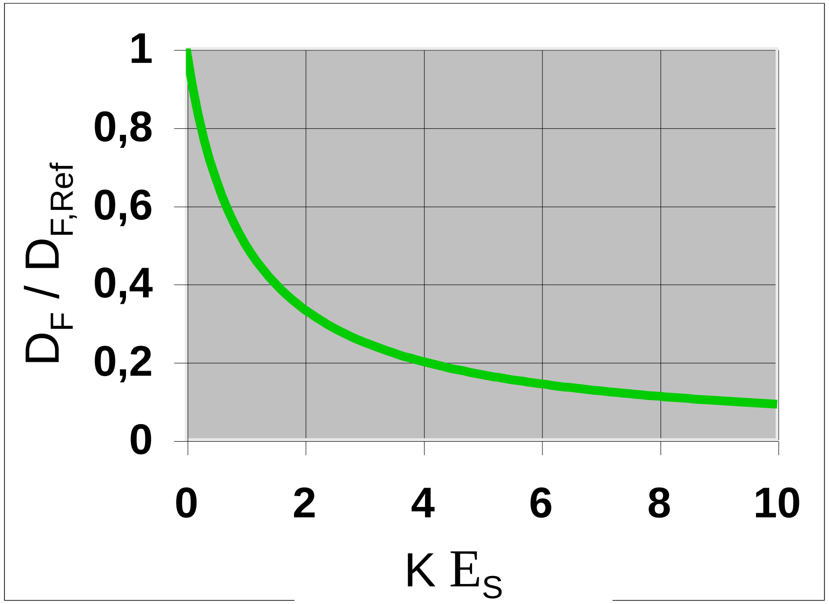
$$E_S = ½\, \rho_o\, \varepsilon^2\, v_{1,y}{}^2$$

the last relation must be modified in such a way that we get:

$$D_F = D_{F,Ref} / [\, (p/p_{Ref})^{\alpha} + K\, \mathrm{E}_S \,]$$

with a suitable constant K and E_S denoting the time average of E_S over one period.

Alternative model to explain the anomalous burning behavior in the perfs



Combining the last equation and the equation for de/dt yields a quite simple expression for the changes of the burning velocity Δ(de/dt) caused by the presence of the ultra sound field characterized by its time averaged acoustic energy density:

$$\Delta(de/dt) = \dot{e}(p_{Ref})\ K\ E_S$$

$$= \dot{e}(p_{Ref})\ K\ 1/T \int E_S\ dt'$$

Alternative model to explain the anomalous burning behavior in the perfs

$$E_S = \varepsilon^2 \, ½ \, \rho_o \, v_{1,y}^{\;2} \approx \varepsilon^2 \, ½ \, \rho_o^* \, c^2 \begin{Bmatrix} \sin^2(k_n y) \\ \cos^2(k_n y) \end{Bmatrix} \sin^2(\, \Omega \, t \,) \qquad \begin{matrix} \text{n odd} \\ \text{n even} \end{matrix}$$

The acoustic energy density does not depend on the „slow time“ anymore which is clearly a consequence of the used approximations.

More important, it shows (as well as the burning velocity change) a phasing which is compliant with the perf shapes experimentally observed.

So, the proposed model which takes into account the impact of the standing ultra sound waves on the thickness of the foam zone is able to explain all experimental observations related to the anomalous burning behavior in the perfs of gun propellants.

Simulation of Closed Vessel Tests with Pressure Oscillations

Simulation of Closed Vessel Tests with Pressure Oscillations

Implementation of the modified burning velocity given before into our closed vessel simulation tool “SimDB” was the easy part of the necessary work.

A little bit more sophisticated was the derivation of information on the growth and absolute values of the amplitudes of the ultra sound field. This was done by treating the gasdynamic equations with a minimum of approximations but never-theless additional assumptions were necessary with respect to the fade away of the oscillations which is not an outcome even of the more detailed treatment.

However, our simulations correspond very well with experimental results as will be shown in the next slides.

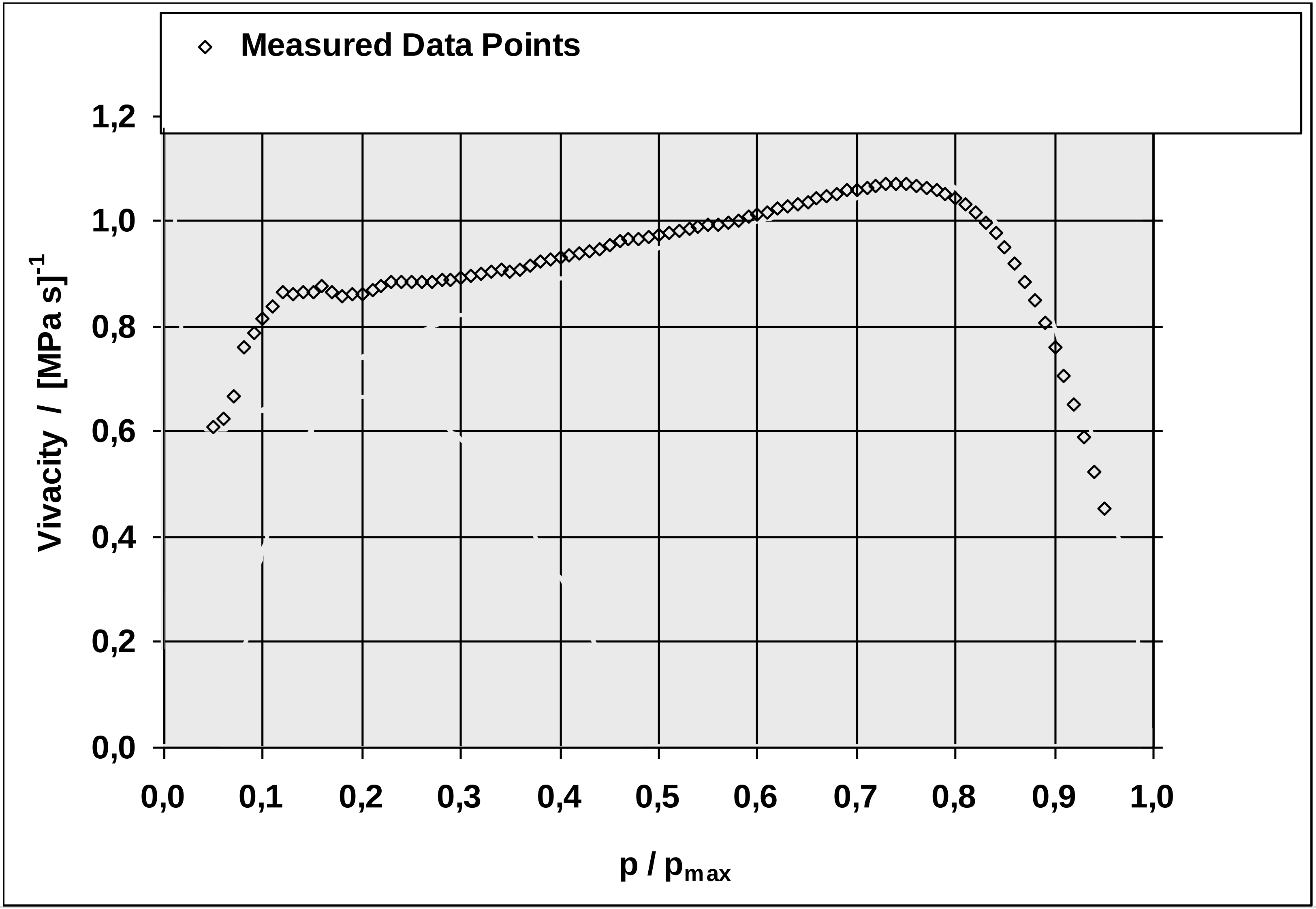
Simulation of Closed Vessel Tests with Pressure Oscillations

As example we take a cylindrical 19 perf gun propellant (length = 12.2 mm, outer diameter = 12.6 mm, perf diameter = 0.19 mm) with conventional L1 recipe which was fired at -40 °C in a 700 cm^3 closed vessel at a loading density of 0.2 g/cm^3. 2 grams of black power were used as ignition charge.

Due to the acoustic hardness of the propellant at cold pronounced pressure oscillations were measured and an anomalous vivacity derived.

Parallel conducted burning interruption test shows a wavelike shape of the perfs with axial mode n = 2 as dominant mode.

Simulation of Closed Vessel Tests with Pressure Oscillations



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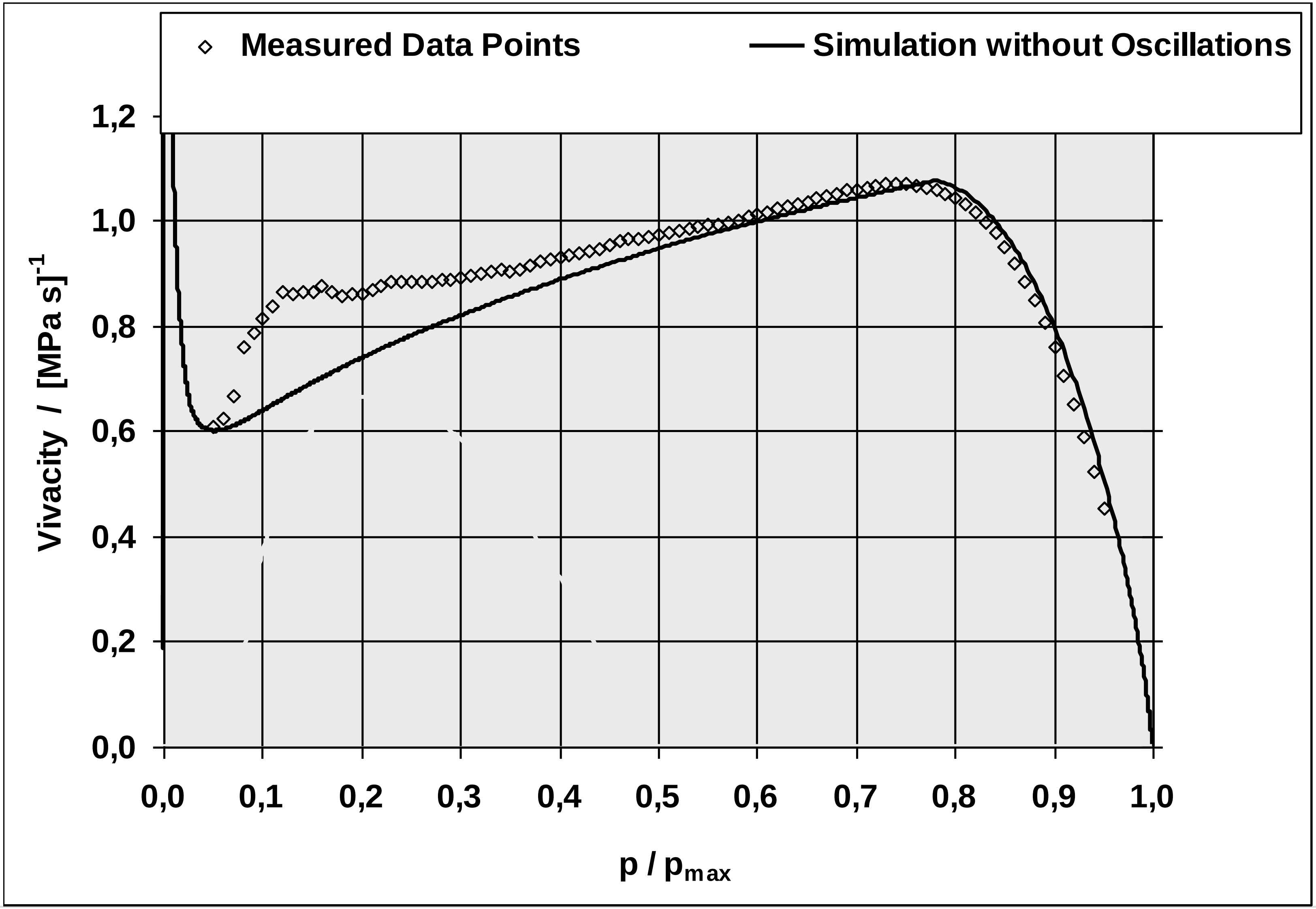

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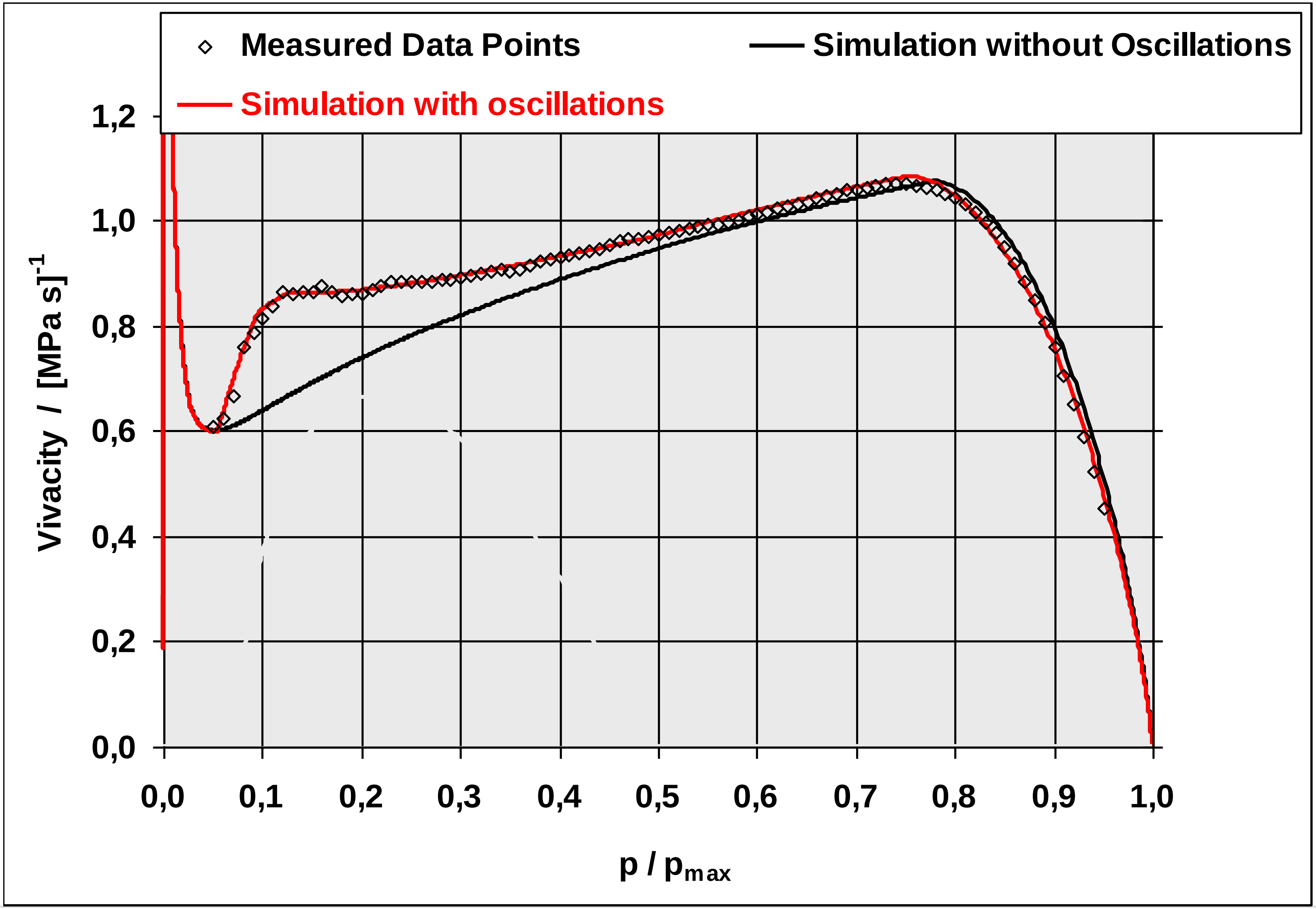

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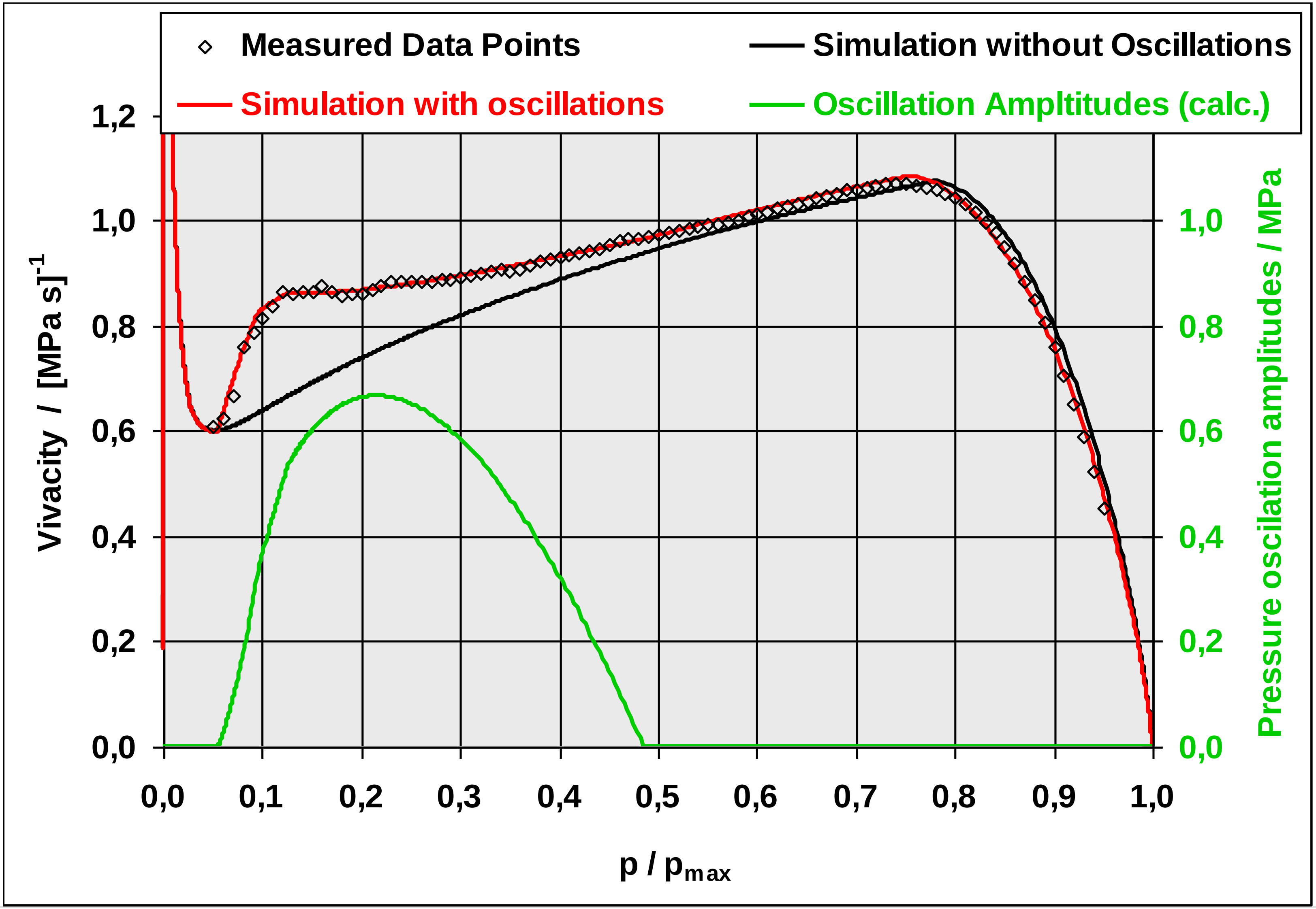

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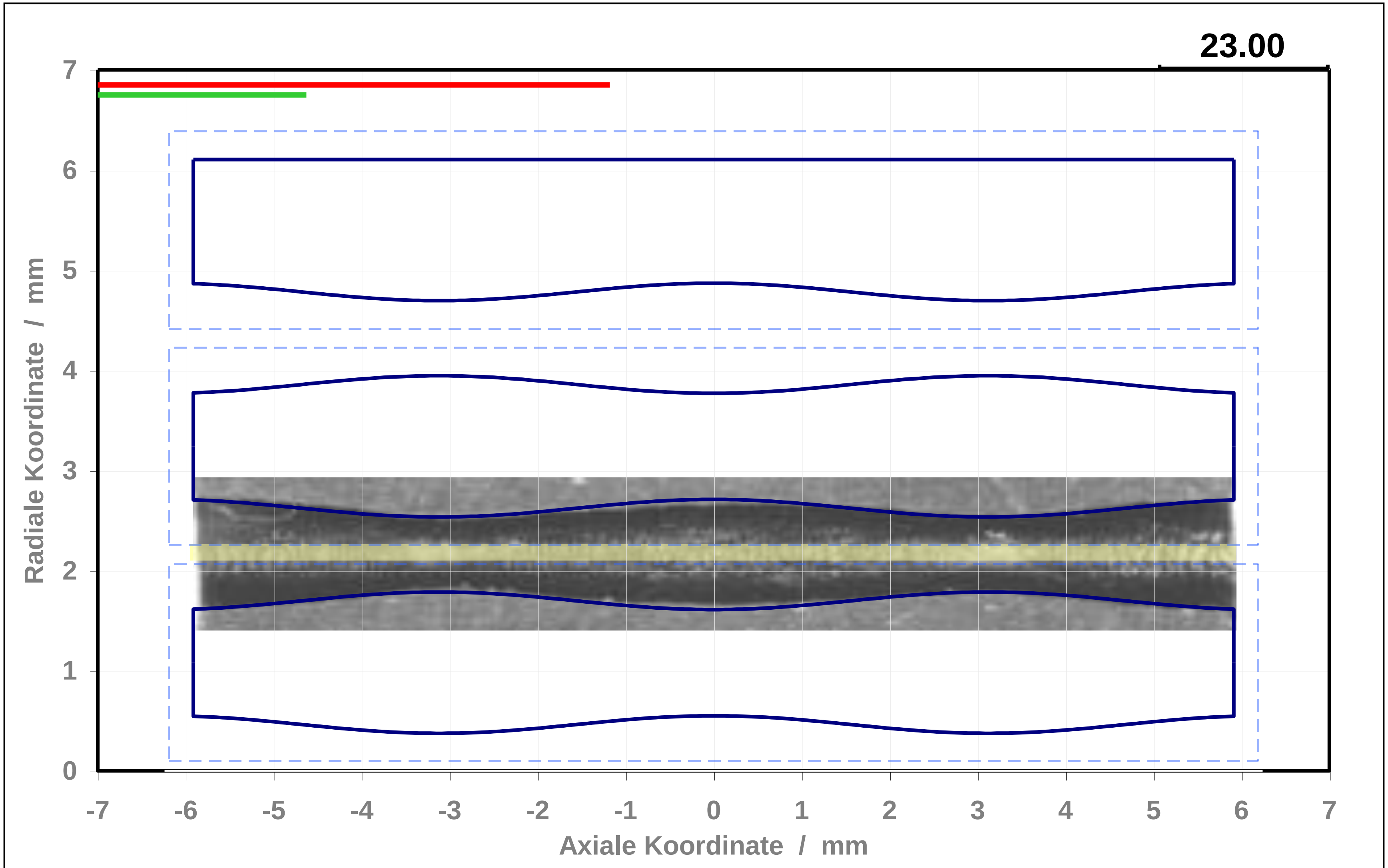

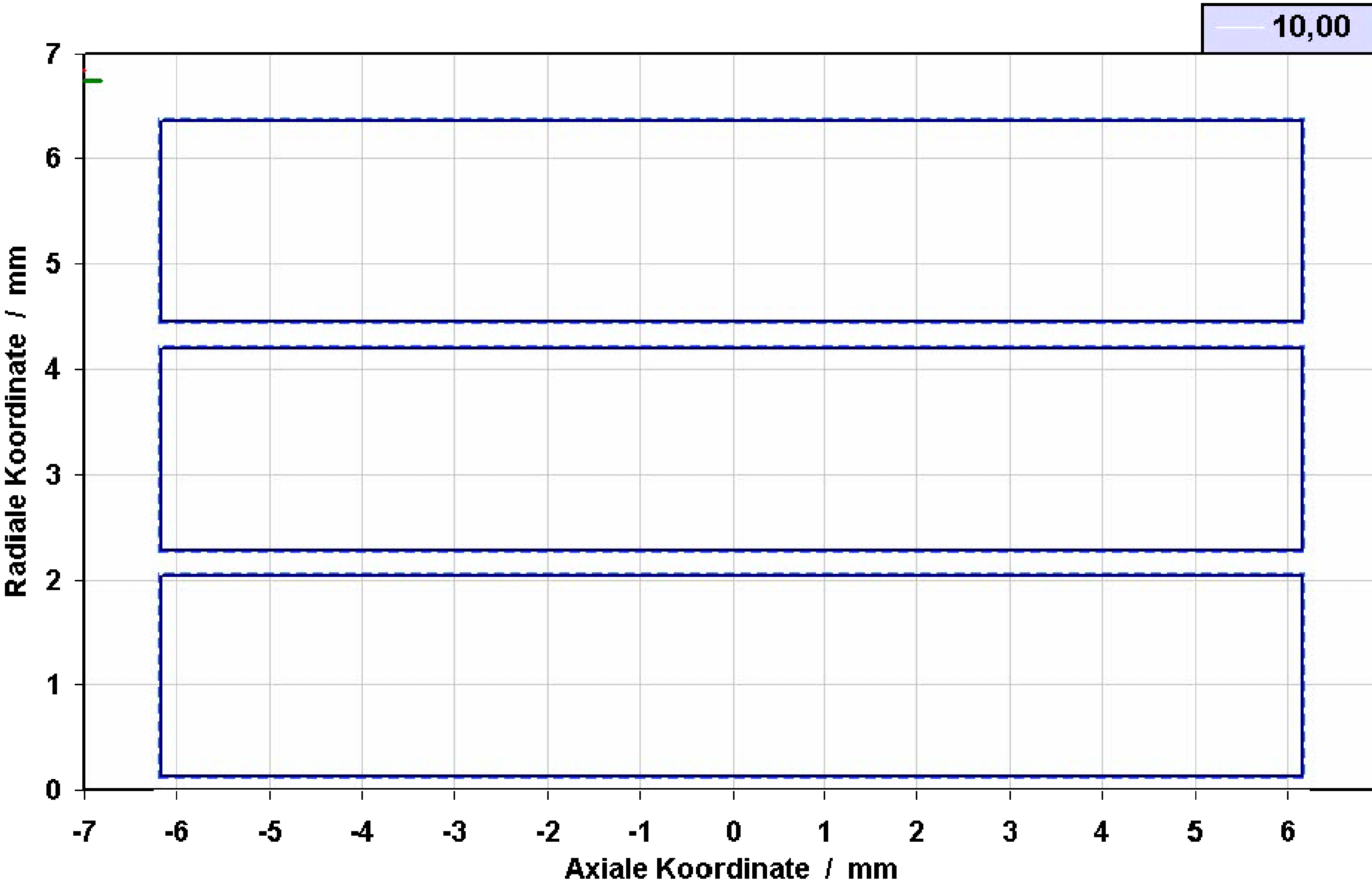
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Summary and Outlook

We have proposed a new approach to explain the impact of density / pressure oscillations on the burning behavior of gun propellants when fired in closed vessels.

The hypothesis is that the ultra sound field related to the standing waves in the perfs causes a reduction of the thickness of the isolating foam zone. As consequence the burning velocity of the propellant is locally increased due to an enhanced heat transfer into the unreacted propellant.

Implementation of this model into our closed vessel simulation tool yields results which are in excellent agreement with experimental observations with respect to vivacity changes as well as the wavelike perf geometries.

Currently we try to extend the model to explain the fine structure which can be seen in the perfs. Feed back of stationary vortices induced by the velocity perturbation on these perturbations seems to be a promising approach.

Thank you

for your

attention !